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A FRAMEWORK FOR THE ANALYSIS OF COGNITIVE TASKS

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A FRAMEWORK FOR THE ANALYSIS OF COGNITIVE TASKS

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A framework for the analysis of cognitive tasks (Een raamwerk voor de analyse van cognitieve taken)

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11 juli 1994, Rapport TNO-TM 1994 B-14

TNO Technische Menskunde[1], Soesterberg

MANAGEMENT UITTREKSEL

De doelstelling van deze studie was de overeenkomsten en de verschillen die er tussen de verschillende typen cognitieve taakanalyses bestaan na te gaan en, indien mogelijk, een theoretisch raamwerk af te leiden, waarbinnen de leemten op onderzoeksgebied zichtbaar worden. Het resultaat van deze studie is een theoretisch raamwerk dat drie perspectieven op cognitieve taakanalyse integreert: taakmodellering, kennismodellering en cognitieve modellering. Elk der drie perspectieven wordt respectievelijk uitgelegd aan de hand van drie prototypische taakanalyse technieken: Hierarchical Task Analysis (HTA), Knowledge Analysis and Documentation System (KADS) and Goals Operators Methods and Selection rules (GOMS).

De perspectieven op taakmodellering en cognitieve modellering zijn reeds bekend in onderzoekskringen van cognitieve taakanalyse. De taakmodellering is gericht op de decompositie van taken in doelen en subdoelen. De cognitieve modellering concentreert zich op de cognitieve performance van de taak. Het perspectief op kennismodellering daarentegen is voor het onderzoeksgebied van de cognitieve taakanalyse een relatief nieuw element.

Binnen het perspectief van de kennismodellering wordt informatie verzameld over de vereisten van de taak; met name over de kennis en de strategieën die nodig zijn om de taakdoelen te bereiken. Deze taakvereisten kunnen een sterke invloed uitoefenen op de cognitieve performance van de taak. Vandaar dat binnen het raamwerk voor cognitieve taakanalyse wordt aanbevolen de taakvereisten te onderzoeken alvorens te beginnen met het analyseren van de cognitieve performance van de taak. Vele typen cognitieve taakanalyses richten zich te sterk op de cognitieve performance van de taak zonder veel aandacht te besteden aan de vereisten van de taak.

Verder onderzoek op dit gebied is dan ook nodig om een brug te slaan tussen de twee kampen van taakmodellering enerzijds en cognitieve modellering anderzijds. Een interessant object voor onderzoek zou kunnen bestaan uit het ontwikkelen van een wijze om de vereisten van een taak op zodanige wijze te verkrijgen dat op grond van deze taakvereisten, samen met de verkregen taakdoelen, voorspellingen kunnen worden gedaan over de cognitieve performance.

[1] Per 1 februari 1994 is de naam Instituut voor Zintuigfysiologie TNO gewijzigd in TNO Technische Menskunde.

CONTENTS Page

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SUMMARY

The goal of this study was to examine similarities and differences between various types of cognitive task analysis and, if possible, to infer some framework in which the areas for further research should become clear. The result of this study is a framework which integrates three views on cognitive task analysis: task, knowledge and cognitive modelling. For each view, prototypical task analysis techniques are presented respectively: Hierarchical Task Analysis (HTA), Knowledge Analysis and Documentation System (KADS) and Goals Operators Methods and Selection rules (GOMS).
The task modelling view and the cognitive modelling view are already known in the cognitive task analysis domain. The task modelling view concentrates on the decomposition of tasks into goals and subgoals. The cognitive modelling view concentrates on the cognitive performance of the task. The knowledge modelling view, however, is a relatively new element in the research area of cognitive task analysis.
Within the knowledge modelling view, it is recommended by the framework to gain information about the requirements of the task. Those requirements can have a strong influence on the cognitive performance of the task and, therefore, within the framework of cognitive task analysis, it is advised to examine task requirements before starting to analyze the cognitive performance of the task. Many types of cognitive task analysis focus too much on the cognitive performance of a task, without paying much attention to the requirements of the task.
Further research in this area is therefore necessary to bridge the gap between one sight of the camp, the task modelling view, and the other sight of the camp, the cognitive modelling view. An interesting work of research could be to invent a way in which task requirements are acquired in such a way that they, together with the task's goals, can easily be used to make predictions about cognitive performance.

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TNO Technische Menskunde[1]
Soesterberg

Een raamwerk voor de analyse van cognitieve taken

E.J.H.M. Merkelbach en J.M.C. Schraagen

SAMENVATTING

De doelstelling van deze studie was de overeenkomsten en de verschillen die er tussen de verschillende typen cognitieve taakanalyses bestaan na te gaan en, indien mogelijk, een theoretisch raamwerk af te leiden, waarbinnen de leemten op onderzoeksgebied zichtbaar worden. Het resultaat van deze studie is een theoretisch raamwerk dat drie perspectieven op cognitieve taakanalyse integreert: taakmodellering, kennismodellering en cognitieve modellering. Elk der drie perspectieven wordt respectievelijk uitgelegd aan de hand van drie prototypische taakanalyse technieken: Hierarchical Task Analysis (HTA), Knowledge Analysis and Documentation System (KADS) and Goals Operators Methods and Selection rules (GOMS).
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Verder onderzoek op dit gebied is dan ook nodig om een brug te slaan tussen de twee kampen van taakmodellering enerzijds en cognitieve modellering anderzijds. Een interessant object voor onderzoek zou kunnen bestaan uit het ontwikkelen van een wijze om de vereisten van een taak op zodanige wijze te verkrijgen dat op grond van deze taakvereisten, samen met de verkregen taakdoelen, voorspellingen kunnen worden gedaan over de cognitieve performance.

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1 INTRODUCTION

The goal of the present report is threefold: firstly, to present a framework of cognitive task analysis unifying the often isolated techniques found in the literature; secondly, to assign different techniques for cognitive task analysis to a limited number of categories; thirdly, to illustrate the use of cognitive task analysis in practice. Until now, cognitive task analysis techniques have been developed ad-hoc, without a framework. This has caused so much chaos, that a clear state-of-the-art review of cognitive task analysis cannot be given. Therefore, first a unifying framework of cognitive task analysis had to be developed. The description of cognitive task analysis in this report is oriented more towards applications than towards fundamental research. This means that methods of cognitive task analysis are only described in relation to theories of cognitive psychology, if results of cognitive psychological research play an important role in those methods. The analysis techniques which are described focus on complex, cognitive tasks which require a higher level of information processing from the task performer than relatively simple, physical tasks.

The global structure of the report can be viewed as follows. Chapter two describes the genesis of cognitive task analysis out of traditional task analysis. Chapter three describes the framework which we have developed to elucidate the area of cognitive task analysis. This chapter is divided into three paragraphs each describing the three views on cognitive task analysis: task modelling, knowledge modelling and cognitive modelling. Chapter four describes three applications corresponding to the three modelling views. These modelling views are described according to prototypical applications: the Hierarchical Task Analysis as a representative of task modelling, the KADS methodology of knowledge modelling and the GOMS methodology of cognitive modelling. Chapter five describes the integration of the three views into cognitive task analysis. Again this chapter is divided into two paragraphs: the first describes the argumentation behind the integration of cognitive task analysis; the second describes the practical consequences of using cognitive task analysis. The last chapter contains a general discussion of the usability of this cognitive task analysis approach and gives some suggestions for further research.

2 WHY COGNITIVE TASK ANALYSIS?

During the last three decades, task environments, task requirements and human performance were analysed to predict or detect problems in task performance and to render solutions to these problems. The kind of analysis that is meant here is called task analysis (Drury, Paramore, Van Cott, Grey & Corlett, 1987; Kirwan & Ainsworth, 1992). Task analysis was used for various purposes: to identify the performance demands of tasks, to identify the skills and knowledge needed to perform the tasks, to calculate the number of persons needed to carry

out a task or to design the interface between human performers and equipment. Good progress has been made on these topics. Depending on the desired purpose of the task analysis a particular technique was chosen. Despite the great variability among task analysis techniques, the techniques did have one important thing in common: they all studied observable behaviour of human performers. Because the overt behaviour of human performers often does not include signs of actual cognitive activity but rather mirrors its results, these techniques concentrate more on the results of the process than on the nature of the process itself. This concentration on the observable behaviour and thus the results of the process, however, made task analysis techniques less usable since the period in which automation of the workplace took place (Moray, Sanderson & Vicente, 1992). This increasing introduction of automation into the workplace has changed the task environments, task requirements and human performance so dramatically that the call for a new kind of task analysis became urgent: the so-called cognitive task analysis.

Replacing human task performers by automation at the workplace has speeded up the call for a cognitive task analysis for the following reasons.

Firstly, routine skills were taken over by machines. As a consequence, many human performers were no longer operating on the task objects and the task process itself but were more-and-more supervising task execution by machines (Moray et al., 1992). This change can be regarded as a change from physical manipulation to mental decision making in human performers. At the lowest level of automation of a system, human performers directly control the hardware and monitor its performance parameters and results by means of displays of sensor outputs, by direct perception or by a combination of these (Drury et al., 1987). With higher levels of automation, human performance requirements become increasingly supervisory in nature, forcing the human performers to continually supervise the processing of the system until a failure occurs. This failure must be recognized, interpreted and compensated for by the human performer, often in a relatively short time limit. In these situations, little emphasis is placed upon the performer's physical manipulation activities as opposed to the performer's mental decision making activities. These mental decision making activities are best analysed by a task analysis which is oriented towards non-observable, cognitive activities.

Secondly, automation has increased and accelerated the stream of information in workplaces. Information, which is at the same time more complex and more diffuse (coming from very different directions), has to be processed by human performers as quickly as before or even more quickly (Helander, 1988; Wickens, 1992). In this context, Wickens describes the example of the transition from driving an oxcart vehicle to navigating a spacecraft. To the oxcart driver, a fraction of a second delay in responding to an environmental event will be of little consequence. But to the navigator of a spacecraft, a delay of the same absolute magnitude may be critical in causing a collision. Considering the

increase in the maximum speed of both vehicles and the increasing chance of errors in human performance, these developments make it very urgent to analyse the operator's cognitive processes quite closely, such as the operator's temporal limits of processing information.

Finally, not only routine skills but complex problem solving as well, is sometimes taken over by machines (Drury et al., 1987). Cognitive tasks of humans have been taken over by knowledge based systems, such as expert systems, intelligent tutoring systems and computer simulations. These systems were developed to support human performance. In order to develop those problem solving machines very intensive studies of the cognitive tasks were required.

To summarise the aspects mentioned above, conventional task analysis is limited in preparing guidelines for designing systems that will help operators as they make judgments and decisions. Automation of the workplace has increased the demand on cognitive skills of human performers. Especially in the domain of system design, the change in focus on cognitive tasks is accompanied by an increasing need for techniques with which these cognitive tasks can be analysed. These cognitive task analyses should allow to analyse complex tasks in which uncertain and dynamic data must be interpreted and assessed. This explains the main reasons why a cognitive task analysis, which is concentrated more on the nature of the process than on the results of the process, was strongly asked for.

3 FRAMEWORK

Now that the importance of cognitive task analysis for various domains has been clarified, the question arises what is understood by cognitive task analysis. A final answer to this question cannot easily be given, because a unique description of cognitive task analysis cannot be found in the literature. In searching through the literature, it became apparent that the term "cognitive task analysis" is used in various contexts, from different perspectives and with variable meanings. The literature search was done on the basis of the following keywords: cognitive processes, task analysis, cognitive task analysis, cognitive model, methodology and combinations of these keywords. The techniques retrieved by the literature search are described in the appendix. A framework that normally represents the context in which the term is embedded and by which the term can be interpreted does not exist. Therefore, in this report, a new perspective on cognitive task analysis is given. A framework is presented in which important views on cognitive task analysis are located. This framework must help to establish a more explicit definition of what is meant by cognitive task analysis and must give a means of comparing the various techniques for cognitive task analysis.

At first sight, the techniques of cognitive task analysis seem to be so diverse that no common characteristics can be defined. After a close examination of the collected techniques, however, three main views can be identified. These views are:

1 task modelling
2 knowledge modelling
3 cognitive modelling.

The main differences among the three views can be characterised as follows. The first view, the task modelling view takes the task as its focus. It gives an answer to the question: "what goals have to be accomplished by performing the task?". The second view, knowledge modelling, takes the task requirements, in terms of the required knowledge and the required strategies, as its focus. The important questions in knowledge modelling are: "which performance norms are given" and "what strategies and knowledge should be used in order to accomplish the goals?". The third view, cognitive modelling, takes the performer of the task as its focus. The central question in cognitive modelling is: "what performance is displayed in practice in order to accomplish the goals?". It gives answers to the question: "what strategies and knowledge are actually used in order to accomplish the goals?".

The distinction between knowledge modelling and cognitive modelling is inspired by Newell (1982; 1992) who put forth several ways of describing problem solving processes, both human and machine. One important way of describing the human is as a knowledge system. He viewed the human considered as a knowledge-level system as having a body of knowledge and a set of goals, so that it takes actions in the environment that its knowledge indicates will attain its goals (cf. Newell, 1982, p.102). A system is intelligent to the degree that it approximates a knowledge-level system. This level, which is called the knowledge level, is comparable to the knowledge modelling view mentioned above. There is a consensus that modelling at the knowledge level is a useful intermediate step in the development of an expert system (Steels & McDermott, 1993). Another important way of describing the human is to describe the way a knowledge-level system is realised in a particular mechanism. This level, which is called the symbol level, is comparable to the cognitive modelling view mentioned above. Physically realizable systems can at best only approximate a knowledge-level system and thus achieve some level of intelligence that is less than perfect. This is because of the computational limits upon the adaptive powers of the system.

Both the knowledge modelling view and the cognitive modelling view can be divided again into two different branches: one that is oriented towards the analysis of procedural knowledge; another that is oriented towards the analysis of declarative knowledge. This distinction will be useful in comparing different techniques of cognitive task analysis with each other.

3.1 Task Modelling

The task modelling view takes the task as its focus. This means that it does not consider the task performer. At this modelling level, it must even be possible to describe the task without knowing what system is chosen for performing the task, a human task performer or some computer system. The task modeller tries to search for answers concerning the goals that should be accomplished by the task. Task modelling is the process of establishing a decomposition of the task into subtasks and the process of establishing the context of the task. The outcome of this process is a task model which contains the tasks and subtasks which have to be carried out in order to accomplish the task's goal. Information concerning the decomposition of the task very often can be found in manuals, educational materials and procedures. Another possibility of information gathering is interviewing people who have information about the task and task environment. These people are, for example, persons concerned with management or people who are responsible for training and education. In any case, these people do not necessarily have to be able to carry out the task themselves. A common way of representing this task model is by describing it in the form of a tree diagram. An important aspect in each task decomposition is to determine to what level the task must be decomposed. This stopping criterion should preferably be determined on the basis of the goal of the cognitive task analysis and on the basis of the type of task domain. Traditional task analysis has become less popular in circles of cognitive task analysis. Some researchers in this area however, still keep up the importance of task analysis, because its information is necessary for specifying task performance requirements and subsequently, cognitive requirements (Essens, 1991). An example of a technique that can be considered a task modelling technique is the hierarchical task analysis (Annett & Duncan, 1967; Sheperd, 1985). This technique will be described later on in this report.

3.2 Knowledge Modelling

The knowledge modelling view takes the task requirements as its focus. Task requirements should be viewed here as the strategies and the knowledge the task performer must use in order to accomplish the task's goal in an optimal way. The important questions in knowledge modelling are: "what performance norms are given" and "what strategies and knowledge are necessary in order to accomplish the goals of the task?". In contrast to the task modelling view, the knowledge modelling view certainly takes the task performer into account in the task analysis. However, the task performer is not regarded as a regular task performer, but he or she is viewed as a genius or a perfectly intelligent system, that is able to retrieve all required knowledge and to execute the required strategies under all circumstances. A task performer who is very experienced in the execution of the task in real life resembles the prototype of the genius most closely. The general question in knowledge modelling concerns the way the goals of the task should ideally be accomplished. This question can be answered by

investigating the two branches of knowledge modelling that have already been mentioned: knowledge modelling which is oriented towards procedural knowledge and knowledge modelling which is oriented towards declarative knowledge. Each of these branches is described separately in the following paragraphs. One common characteristic, concerning the practical usage of the two branches of knowledge modelling is the time-consuming process of applying a knowledge modelling technique to a task domain as a whole. Therefore, in knowledge modelling, one subtask of the task is very often selected and the modelling technique is applied to this subtask alone. The selection of the subtask mostly depends on the objective of knowledge modelling. Take the medical domain as an example, in which the final goal of knowledge modelling may be developing a knowledge-based system that should support the physician with diagnosis. In this case the subtask of "diagnosis" is selected and taken for further knowledge modelling investigation. Subtasks such as "performing tests" or "prescribing medication" are not selected, because these subtasks, in this example, are not supported by a knowledge-based system.

a. Knowledge Modelling focusing on procedural knowledge

This branch of knowledge modelling tries to give answers to the way the task's goals should ideally be accomplished by focusing on the most optimal procedural knowledge that is required to carry out the task. Procedural knowledge is defined here as mental representations consisting of an ordered series of steps for accomplishing a task's goal. Experts are regarded as important information sources in knowledge modelling, because they are the ones that most likely take the optimal strategies in carrying out the task. Information about required strategies or sequences of steps belongs to the procedural task information which often cannot be found on paper. Therefore research on artificial intelligence strives for identifying and registrating generic strategies in common types of problem-solving tasks; the so-called generic tasks (Chandrasekaran, 1983). With the aid of a library of generic tasks the identification of strategies of new tasks, assumed to be examples of generic tasks, can be speeded up (Schaafstal & Schraagen, 1992).

Generic tasks can be defined as general categories of tasks, which group particular tasks together because of their corresponding problem solving characteristics. This means, for instance, that tasks which belong to the same generic task have the same global characteristics of the problem, the same global characteristics of the solution and the same global characteristics of the process of finding one or more solutions (the strategies). The generic task categories which have already been defined, include classification, assessment, diagnosis, design, configuration and planning (Schreiber, Breuker & Wielinga, 1993). Identification of a task as an example of a generic task takes place if task characteristics of the particular task at hand match against characteristics of a generic task. An example of this matching process can be given by the identification of the task of contracting a person as a generic assessment task or the task of troubleshooting in a technical system as an example of the generic diagnosis

task. Another example of a generic task is hierarchical classification, that uses the "establish and refine" method and assumes the existence of a classification hierarchy. The underlying idea is that generic tasks can be combined in order to solve more complex tasks.

b. Knowledge Modelling focusing on declarative knowledge
This branch of knowledge modelling specifically focuses on declarative knowledge that is required in order to accomplish the task's goals. Although this kind of research can more easily profit from written information about required knowledge, in this modelling view, experienced task performers are of great value too; especially if written information is lacking. Describing knowledge on the level of the knowledge models, means that the knowledge modeller identifies the views that can be put upon the way the domain concepts are related and the organisation of concepts and relations. If a generic task category has been identified for a certain task, the views with which the task domain is approached can be more easily identified as well. Another word for "perspective" in this context is "domain model" or "knowledge model". Different types of domain models can be identified. Examples are: structural, behavioural, functional, topological, fault models, component models, etcetera. Trying to match the specific task of troubleshooting, as mentioned above, one could identify this task as a diagnosis task. In diagnosing a technical system, the functional model and the component model, for instance, lend themselves well to reason about the system faults. A lot of progress has been made in artificial intelligence in this area of research (Steels, 1992; Benjamins, 1993).

3.3 Cognitive Modelling

Cognitive modelling takes the performer of the task as its focus. The important questions in cognitive modelling are: "what performance is displayed in practice in order to accomplish the task's goals" and "what strategies and knowledge are actually used in order to accomplish the task's goals". In contrast with knowledge modelling, not only the genius or expert task performer is used as single human information resource but the less experienced task performer or even the beginner are used for this purpose as well. However, here the expert is not considered as a perfectly intelligent system but as a task performer who can also make mistakes while carrying out his task and especially these mistakes are investigated thoroughly in cognitive modelling. To clarify the difference between knowledge modelling and cognitive modelling, one can think of knowledge modelling as a description of the performance norms and of cognitive modelling as a description of the actual performance itself. The performance norms discuss the way the task's goals should ideally be accomplished, whereas the description of cognitive performance discusses the way the task's goals are, or are not, accomplished in practice. Knowledge modelling views performers as perfect systems that are not hampered by any kind of limitation of information processing. Cognitive modelling views human performers as systems endowed with

limitations on their information processing, for instance human performers cannot always perform tasks perfectly because of their limited working memory. Cognitive modelling can also be divided into two branches which correspond to the branches identified in knowledge modelling: cognitive modelling oriented towards procedural knowledge and cognitive modelling oriented towards declarative knowledge.

a. Cognitive Modelling focusing on procedural knowledge
This branch of cognitive modelling turns the interest to the study of procedural knowledge that are used in practice to carry out a task. A cognitive modeller tries to analyse the various strategies that are actually used by expert and less experienced task performers in carrying out their task. In this branch, verbal protocol analysis is often used as a method for obtaining procedural knowledge (Ericsson & Simon, 1984). Protocol analysis is a technique for analysing verbal protocols, obtained from task performers thinking aloud while carrying out their task. Hence, protocol analysis is not based on what task performers themselves think they are doing while carrying out their task but rather on the actual verbal statements that are taken as data. These data are used for testing hypotheses on the presumed procedural knowledge that underly the observed cognitive behaviour. In this area much research is being done concerning the differences between novices and experts (Schraagen, 1993). Human limitations are taken into account in producing the cognitive model. The modeller studies the human performer's way of "walking through" the task tree, created during task modelling, and represents those strategies as a kind of cognitive path. For instance, Schraagen (1993) found that experts, when designing experiments, used a structured approach to solving both novel and routine problems, whereas novices used a quasi-random approach. Experts started by an elaborate problem orientation phase, whereas novices jumped right in the middle of the problem. In the domain of diagnosis, Schaafstal (1993) found differences in procedural knowledge of experts and novices diagnosing a fault in a paper mill. In this domain as well, experts have a much more structured approach to diagnosis than novices, who often forgot to consider the seriousness of the problem or to evaluate their solution. An example of a technique at the level of cognitive modelling is the method of analysing Goals, Operators, Methods and Selection Rules (GOMS) (Card, Moran & Newell, 1983). This technique is discussed later on in this report.

b. Cognitive Modelling focusing on declarative knowledge
This branch of cognitive modelling is concerned with the analysis of declarative knowledge which are used in practice to carry out a task. The different types or models of knowledge are investigated thoroughly on this level of cognitive modelling; it is, for instance, analysed whether a task performer uses a causal model to solve a particular problem, instead of the prescribed functional model. Various knowledge elicitation techniques may be employed in order to derive declarative knowledge: psychological scaling techniques (Schvaneveldt, Durso, Goldsmith, Breen & Cooke, 1985; Cooke & McDonald, 1987) such as multi-

dimensional scaling (Kruskal, 1964); sorting techniques such as, hierarchical clustering schemes (Johnson, 1967) and multi-trial free recall (Reitman & Rueter, 1980); eliciting semantic relations for networks (Cooke, 1993); eliciting information on the basis of "limited-information tasks" (Hoffman, 1987); interviewing techniques, which make use of domain-related cues, such as critical incidents analysis (Flanagan, 1954) and repertory grid analysis (Boose, 1985) and, to a lesser extent, think-aloud protocols and retrospective analysis (Ericsson & Simon, 1984).

4 APPLYING THE MODELLING VIEWS IN PRACTICE

Now that the relevant aspects of the three modelling views are described, the practical usage of each modelling view will be elucidated according to three prototypical applications: HTA as a representative of task modelling, KADS as a representative of knowledge modelling and GOMS as a representative of cognitive modelling.

4.1 Task Modelling: HTA

Hierarchical Task Analysis (HTA), first described by Annett and Duncan (1967), is a formal method for structuring information about the total task which a human has to perform. HTA is a form of task analysis which tries to reveal the goal-directed behaviour of the human. The central concern of HTA is the decomposition of a systems task into operations (or subtasks) linked by plans. The fact that HTA tries to decompose a human's task into operations, makes it an example of a task modelling technique. The aspect of linking these operations into plans, makes it also a candidate for a knowledge modelling technique, which is concentrated on identifying procedural knowledge. The hierarchical decomposition of the task is, however, emphasized most and therefore it can be considered from the task modelling view for the greater part.

In decomposing the task, HTA tries to divide the operations into its constituent sub-operations, as long as the sub-operations are mutually exclusive and together form the higher-order operation. The original version of HTA advised general "stopping rules" to apply at the decomposition process but the current version is influenced more by a pragmatic point of view and advises the task analyst to stop the decomposition process when further decomposing would have no profit to the task analyst. In HTA it is common to analyse some parts of the task in detail (they are further broken down in operations) and other parts of the task only superficially. The output has a standard format: a tree diagram. This tree diagram presents the operations in their relative positions to one another.

Crawshaw, Healey, Hockey and Lambert (1993) used HTA as one of the sources of information to analyse the task of a watchkeeper on a ship's bridge. The goal of analysing this task was to devise scenarios which were to be used in a simulation programme of the task. The analysts retrieved information for the HTA from literature, from their own observational experiences and from interviews with numerous seafarers. A part of the tree diagram of the navigation task of the watchkeeper is shown in Fig. 1. This figure illustrates the decomposed task of the watchkeeper into four subtasks: "avoid grounding" (3.2.1), "avoid collision" (3.2.2), "avoid adverse weather effects" (3.2.3), and "control ship course and speed" (3.2.4). The figure shows that the subtask of avoid collision (3.2.2) is further analysed and broken down into six subtasks.

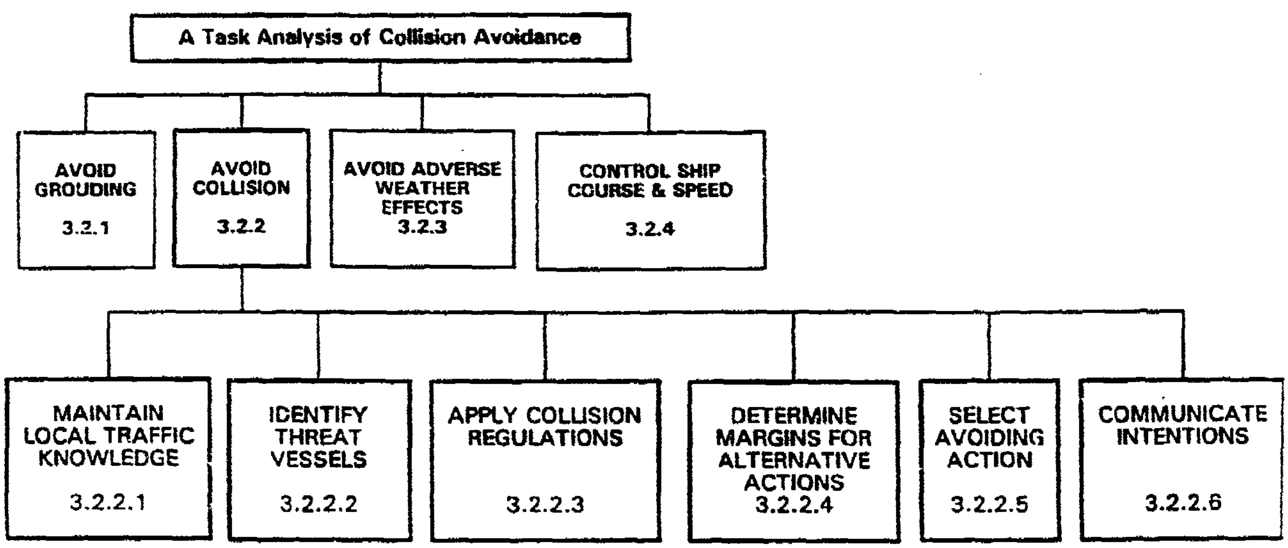

Fig. 1 Example of an outcome of an HTA for the navigation task of a watchkeeper on a ship's bridge.

One of the advantages of HTA as a task modelling technique is that it gives the task analyst a clear overview of the context of the task and of its requirements. In cases in which the improvement of only one subtask is aimed for, it makes more sense to know the other subtasks which are necessary to accomplish the task goal as well. One could, for example, easily imagine that the most optimal change in the process of accomplishing a task goal is not realised by the improvement of only one subtask but is realised by a reorganisation of other subtasks. However, in practice the hierarchical decomposition is not always applied to the total number of operations but more often to a specific part of the task. One of the disadvantages of HTA is that the validation of the method is difficult because different people might decompose a task in different ways. So one may doubt the normative character of the task description, if HTA is used as a task modelling technique. Therefore it is not surprising that sub-operations can be devised according to subjective elements or that sequences of operations

can personally be determined. It seems, therefore, wise to have multiple analysts independently carry out an HTA, and resolve disagreements by discussion. Also, the outcome of an HTA should be checked thoroughly with experienced task performers or educators and improved upon in an iterative fashion.

4.2 Knowledge Modelling: KADS

Knowledge modelling that is oriented both towards procedural knowledge as well as towards declarative knowledge is possible within one kind of modelling technique. An example of such a modelling technique is the method of Knowledge Analysis and Documentation System (KADS) (Schreiber et al., 1993). KADS models knowledge in terms of generic tasks and in terms of standard organizations for declarative knowledge and is used for the development of knowledge-based systems. The importance of generic tasks in KADS is that it allows the system developer or knowledge modeller to make use of established patterns of knowledge use (making inferences) and, secondly, to use generic tasks in interpreting verbal data. This technique which is characterised as a task oriented approach (Benjamins, 1993), tries to find out which performance norms are prescribed and what strategies and knowledge should be used in order to accomplish the task's goals. Task oriented approaches try to model problem solving in terms of the knowledge that is used for the problem solving. This knowledge is organised and represented by generic tasks (e.g. diagnosis, repair, configuration).

KADS is a knowledge modelling technique that is used to model problem solving by identifying tasks at various levels of abstraction. Despite the fact that KADS is often used to develop knowledge-based systems, modelling expertise in KADS is done independent of implementation aspects. The outcome of KADS is the so-called "model of expertise". This model is constituted by four different types of knowledge: domain knowledge, inference knowledge, task knowledge and strategic knowledge. These different types of knowledge (in KADS terms: "layers") are used to gather and structure the knowledge. Because in this research area the knowledge gathered on problem solving comes from various information sources (written materials or human experts) and is often not complete, KADS uses generic tasks (in KADS terms: "interpretation models") in order to identify the particular type of problem solving. If a particular task is matched against a generic task, the acquired knowledge can more easily be interpreted and structured.

The underlying idea here is that the problem-solving process in even different domains can be characterised by the same underlying patterns of inference and interpretation. A generic task or interpretation model shows which reasoning steps are to be followed to solve a problem in a given type of problem. From these interpretation models one can derive at which points in the reasoning process information is needed, information must be calculated, solutions are

generated and selected, etcetera. From the perspective of re-usability and maintenance a library of generic components is built for the knowledge engineer. In the new version of KADS which is still under development, named CommonKADS, re-usable structures of domain models (ontologies) are searched for (Benjamins, 1993); these models show the type of objects within a given problem domain on an abstract level and the type of relations that must exist between those objects. This ontological knowledge could, for example, help students in training troubleshooting in technical devices (teaching system knowledge on a functional level).

An example of an application of KADS is the Sisyphus project in which KADS has been used to the office assignment problem (Schreiber et al., 1993). This problem can be described as allocating rooms to employees, while satisfying numerous constraints, such as the limited number of rooms (compared with the number of employees), professional peculiarities and personal preferences. The final products of this project were a model of expertise and a design for the application. The problem solving task that was modelled consisted of assigning rooms to employees. Firstly, a description of the major entities (employees, rooms, projects) and relationships (hierarchies, project assignments, floor plan) in the domain was created to gather declarative knowledge. Secondly, a think-aloud protocol was produced, which showed how an expert solves a particular office assignment problem, to gather procedural knowledge, such as the task structure shown in Fig. 2 which is based on the think-aloud protocol. It shows how particular elements (components, plan, etc.) are used in a systematic way by particular processes (assemble, select, etc.).

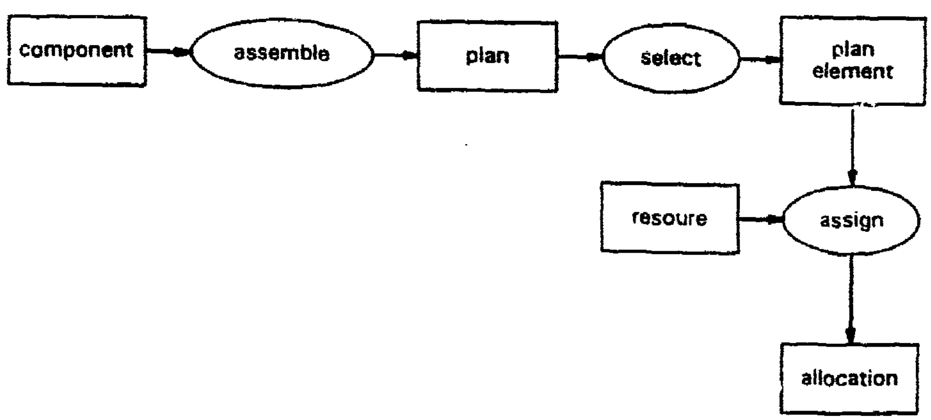

Fig. 2 Example of a task structure created by using KADS techniques to gather inference knowledge about the office assignment problem.

Thirdly, the protocol was used to form some idea about the nature of the task and to investigate whether it resembled some known (generic) task. Fourthly, the office-assignment task was classified as a design task; although the solutions are in principle enumerable for a given input problem, in practice the solution is not

selected, but constructed as in other design problems. The task was further specified to the routine task of allocation and the corresponding methods and inferences were analysed. On the basis of this interpretation model, more knowledge was acquired and the model of expertise was constructed. Finally, the behaviour of the system which was specified in this model of expertise was implemented.

One of the advantages of KADS as a knowledge modelling technique is that it makes use of existing models of problem solving in acquiring specific task characteristics and task requirements. KADS has recognized that performance norms are lacking very often or are written down only partly. Therefore KADS strongly turns to other resources of information to acquire procedural knowledge and declarative knowledge. If written information is lacking, KADS analyzes the problem solving performance of experts in order to abstract from this performance to one or more of the generic models of problem solving. The generic model of problem solving then is filled in with task specific knowledge and taken as a kind of normative performance model. One of the disadvantages of KADS as a knowledge modelling technique is that it is a very time consuming process to execute the methodology. KADS is primarily developed to acquire knowledge in a more structured way in order to develop more stable and fundamental knowledge-based systems. The methodology asks from the analyst that the problem solving task is worked out in such a detail that a knowledge-based system can be designed upon this outcome. This means that the system must be able to function as an intelligent system being flexible enough to reason with different kinds of knowledge and being able to make different kinds of inferences. In order to gain better insight in the cognitive performance of a human task performer, it is not necessary to model completely the performance of a system which is not hampered by human information processing limitations. KADS focuses too much on the development of knowledge-based systems to be directly useable for cognitive task analysis.

4.3 Cognitive Modelling: GOMS

The GOMS method (Card, Moran & Newell, 1983) is a technique that is aimed at modelling the human performer. The acronym GOMS stands for Goals Operators Methods and Selection Rules. GOMS is a task analysis method which tries to identify the methods, operators and selection rules that are used by the human task performer in order to accomplish his or her goals. This means that GOMS focuses on the knowledge a user must have about the methods, operators and selection rules or, in other words, the "how-to-do-it" knowledge. One could say that this knowledge is the user's representation of the task. Modelling this "how-to-do-it" knowledge corresponds to the view of cognitive modelling, which tries to give answers to the question: "what strategies and knowledge are actually used in order to accomplish the task's goals?". GOMS explicitly acknowledges

cognitive limitations on task performance, such as working memory limitations and deficiencies in knowledge of methods for carrying out tasks.

The goals, operators, methods and selection rules together form a representation of the "how-to-do-it" knowledge. A goal is a symbolic structure that defines a state of affairs to be achieved and determines a set of possible methods by which it may be accomplished. Goals and subgoals are both hierarchically and sequentially related to each other, so that the complete goal structure specifies the conceptual and the temporal relationship among the various component tasks. The goal structure is considered the plan of the human performer for carrying out the complete task. In this sense, the goal structure is identical to what we have called a "task structure". Operations are defined in this system as mental representations of the various elementary functions and other cognitive operations that are performed during the execution of the task. Methods are procedures for satisfying specific goals and subgoals. Selection rules are used to specify what methods should be used to satisfy a given goal or subgoal in a specified context. When several methods are available with different characteristics that can satisfy the same goal, selection rules are used to pick out the method that is appropriate to a specific context. These definitions clearly indicate that GOMS focuses more on procedural knowledge than on declarative knowledge.

As an example of a GOMS model, imagine the user goal of deleting a file in file manipulation tasks in Macintosh Finder. In order to accomplish this goal a method is described which is an explicit step-by-step description of what the user has to do.

Method for accomplishing goal of deleting a file
    Step 1: accomplish goal of dragging file to trash
    Step 2: return with goal accomplished

Because in Macintosh Finder generalized methods can be found in order to accomplish various goals, a general submethod corresponding to the drag operation is defined.

Method for accomplishing goal of dragging item to destination
    Step 1: locate item for item on screen
    Step 2: move cursor to item icon location
    Step 3: hold mouse button down
    Step 4: locate destination icon on screen
    Step 5: move cursor to destination icon
    Step 6: verify that destination icon is reverse-video
    Step 7: release mouse button
    Step 8: return with goal accomplished

In this example, goals, methods and operators are described; selection rules, however, are not inserted. A selection rule can give the performer the choice of, for example, taking a shortcut of operators, to take an alternative sequence of operations etcetera. These terms are not further explained here; for a full description see Card et al. (1983). One important characteristic of a GOMS model, however, still has to be mentioned. It is the fact that the "how-to-do-it" knowledge is described in a form that can be executed by a human being or a computer program (the program can be implemented in production rules). Going through the GOMS description the actions are executed and the task is actually carried out. The goal of describing the knowledge at such a low level is to derive execution times and predictions of learning by counting the number of statements or production rules.

GOMS may be viewed upon as a representative of cognitive modelling which is one of few methods which does take the analysis of the user's representation of the task into account. One could, however, doubt whether GOMS is a purely cognitive modelling method in the above sense of the word. In order to be able to produce a user's representation of the task, the job task and its environment are represented. Identifying and defining the user's goals is said to be difficult (Kieras, 1993), because the analyst must examine the task that the user is trying to accomplish in such detail that he or she often has to go beyond the specific system to the context in which the system is being used. This seems to correspond to our definition of task modelling. Furthermore, the user's goals are not derived from the user directly or even from the user at all but they are often just speculated upon by the task analyst. In situations in which the majority of the goals is device-dependent they are relatively easy to define. Device-dependent or device-specific goals are things that a user must accomplish because of the design or nature of the device. However, in situations in which natural goals are important too, the job is more difficult to a task analyst because these goals are not device-dependent but rather user-dependent (depending on the user's prior experience with corresponding systems for instance). In order to reflect the user's concept of the system, the analyst must attempt to identify the natural goals that the users have. This process can better be called judgment calling than cognitive modelling. An example of a judgment call for moving text in the text processing program MacWrite, is that the user views moving text as first cutting, then pasting, rather than as a single unitary move operation. So at the same time this feature of GOMS is one of the weak aspects of the method, because from a cognitive modelling point of view it is not appropriate for the analyst to make assumptions about how humans view a task or a system. This critique is countered by GOMS adherents who argue that it is not practical to collect data on how users view and decompose tasks.

Therefore, it is suggested here that the theoretical basis of the GOMS method can be seen as contributing to the cognitive modelling view but the practical usage of GOMS makes it belong to a knowledge modelling technique. Another practical problem, which makes the cognitive modelling view of GOMS doubtful,

is the fact that many cognitive processes are too difficult to analyze in a practical context. This problem is even agreed upon by GOMS adherents. Examples of such cognitive processes are reading, problem-solving, debugging, and so forth. The solution which the GOMS method offers to this problem is to simply bypass a complex process by representing it with a "dummy" or "placeholder" operator. Representing a bypassed process consists of using an analyst-defined operator together with information in the task description as place holders to document that the process is taking place and what its assumed results are. In other words, GOMS can produce not many cognitive modelling results in tasks which consist of lots of complex processes. It is not surprising that most of the GOMS applications are restricted to modelling micro- or low-level processes which demand little effort from human cognition. Therefore GOMS has mostly been used for analysing expert behaviour in routine-like tasks.

An example of an application of GOMS is the Ernestine project (Gray, John & Atwood, 1992, 1993). In this project, GOMS was used to test its applicability to real-world design problems. GOMS models were defined here to predict the performance of the toll and assistance operator (TAO) using a new workstation. The TAO is the operator you get when you dial 0. Their job is to assist the customer in completing calls and to record the correct billing. Among other tasks, TAOs handle person-to-person calls, collect calls, calling-card calls, and calls billed to a third number. The goal of using GOMS was to evaluate two TAO workstations—a current workstation and a proposed workstation.

With the help of Operator Services Personnel relevant and common procedures executed by the TAOs were depicted and used as benchmarks for modelling. To model these benchmarks two different approaches were used: observation-based models of performers interacting with the current workstation and models based on the specifications of the proposed workstation. Because the TAO's task is characterised by doing several things in parallel when processing a customer's request CPM-GOMS was used to display these parallel activities and to calculate total task times (John, 1988).

CPM-GOMS is an extension to GOMS which distinguishes among Cognition, Perception and Motor operators and uses the Critical Path Method (developed for project management). The critical path is an important concept in analysing the total task time for complex parallel tasks. When activities occur in parallel one sequence of activities will take more time than parallel sequences of activities; the critical path is the sequence of activities which takes the longest and determines the total time for the entire task. In CPM-GOMS the parallelism of the task is represented in a schedule chart (see Fig. 3).

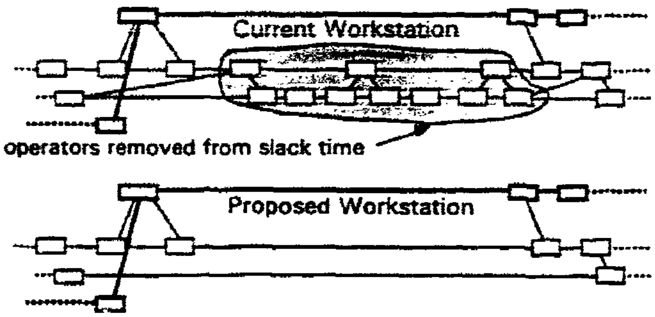

Fig. 3 Example of a section of a schedule chart created by using CPM-GOMS techniques to evaluate two different workstations. From this part of the call the proposed workstation (bottom) has removed two keystrokes which had required seven motor and three cognitive operators. However none of the ten operators removed were along the critical path (shown in bold).

In this chart each activity in handling a call is represented as a box with an associated duration. Dependencies between activities are represented as lines connecting the boxes. The critical path is also displayed in this chart (bold lines). The boxes and their dependency lines are drawn according to a detailed understanding of the TAO's task and goal decomposition (John, 1990).

As a result of the analysis, the CPM-GOMS models predict that the proposed workstation will be 3% slower than the current workstation. These results were consistent with the empirical data obtained later on from a field trial. The reason why the proposed workstation was slower than the current workstation was explained by CPM-GOMS as follows. Although the proposed workstation generally had fewer keystrokes than the current workstation, the new procedure put more keystrokes on the critical path, especially to the end of the call, rather than in the slack time, increasing the length of the call. In addition, in the proposed keyboard the close spacing of the keys encouraged the right hand to press all keys; CPM-GOMS predicted that this would be slower than the old procedure of using the left hand for certain keys. These two examples make clear that CPM-GOMS correctly predicted the proposed workstation to be slower, while the manufacturer predicted that the proposed workstation would be faster than the current workstation. Based on the GOMS task analysis, the phone company had to reconsider the investment of the proposed workstation.

One of the advantages of GOMS as a cognitive modelling technique is that it allows to predict performance in human-computer interactions very accurately. If human-computer interaction tasks make an appeal to micro- or low-level processes for the greater part, then GOMS is a very good predictor for human performance. However, at the same time this advantage could be seen as a disadvantage, because GOMS is not good at predicting human performance if tasks are not routine-like but have a more problem solving character and make

an appeal to higher, cognitive, processes problem solving tasks. For these kind of cognitive and dynamic tasks GOMS is not suitable.

5 INTEGRATION OF THE MODELLING PERSPECTIVES

Now that the three modelling views are described according to their prototypical applications, this chapter turns to the integration of those views into cognitive task analysis. Firstly, the argumentation behind the integration of cognitive task analysis is given. Secondly, an example of cognitive task analysis as it could be used in practice is given.

5.1 Cognitive Task Analysis

Cognitive task analysis (CTA), as we define it, is a form of analysing a task which consists of the three views together: task modelling, knowledge modelling and cognitive modelling. If only one of these views is used, it cannot be called a cognitive task analysis. An analysis, for instance, which only contains cognitive modelling does not gather enough information about the task, the task environment and the task requirements. The same can be said for the other two views if they are used in separation. Because a cognitive task analysis must minimally be able to gather information about the task, the task environment, the task requirements and the human performance of the task, all three modelling views are important.

The order in which these three forms of modelling can best be used is an order in which task modelling is the first modelling activity, knowledge modelling the second and cognitive modelling the third activity. This order is argued for because analysing and interpreting human task performance (cognitive modelling) is hardly possible without knowing the task, the subtasks, the task environment (task modelling) or without knowing the requirements of the task (knowledge modelling). Without knowledge modelling, it is also difficult to imagine what interpretation can be given to the output of cognitive modelling. In the literature the term cognitive task analysis is often misplaced: in situations in which in fact only cognitive modelling has taken place, researchers do refer to the method as cognitive task analysis.

However, although the framework for the analysis of—and examination of—cognitive tasks helps to establish a more explicit definition of what is meant by cognitive task analysis, it causes practical problems at the same time. A consequence of defining cognitive task analysis as we do could have some practical problems, because the process of modelling the task, the knowledge *and* the human cognition could ask more time than was expected before. Therefore, we advise to consider the final goal of the analysis in practice

thoroughly, before using various modelling techniques in order to gather information about the task. If one has to know more about the task, the decomposition of the task into suotasks or about the task environment, one can confine oneself to task modelling. In this case, however, one cannot call this kind of modelling a cognitive task analysis. If one wants to know, however, which strategies and which knowledge are necessary to carry out the task or subtask, the application of knowledge modelling is required after a task modelling has been applied. Again one cannot call this kind of modelling a cognitive task analysis. Only if one wants to know whether the prescribed strategies and knowledge are actually used by a human task performer, it is necessary to finish the two preceding steps with cognitive modelling. In this case one can call the analysis a cognitive task analysis. It is possible that cognitive modelling is used by itself and that its results are sufficient to the goal of the analysis; in these cases, however, we prefer to call this kind of analysis, in which the task is not studied in a detailed way, cognitive modelling or cognitive analysis.

Summing up, cognitive task analysis can be viewed from three main views: the task modelling view, the knowledge modelling view and the cognitive modelling view. In contrast to the latter two views, a task modelling view emphasizes the task itself and does not consider the task performer. Task modelling is the process of establishing a decomposition of the task into subtasks and the process of establishing the context of the task. The other two views, knowledge modelling and cognitive modelling, do, however, often start with the task performer. Intelligent systems, such as human task performers, can be described at either of these levels. A knowledge level description emphasizes the knowledge contents of a system (e.g., goals, actions and knowledge used in a rational way), whereas the symbol level describes its computational realization. This means that knowledge modelling tries to find out which performance norms are prescribed and what strategies and knowledge should be used in order to accomplish the task's goals, whereas cognitive modelling tries to find out what performance is actually displayed in practice in order to accomplish the goals.

5.2 Cognitive Task Analysis in Practice

A complete application of cognitive task analysis, as it is meant by the framework, cannot be found. Therefore an example of an integrated version of cognitive task analysis is described here. As an example of a domain to which the cognitive task analysis could be applied, the orthopaedic shoe technician's task is chosen. The orthopaedic shoe technician's task is meant to provide orthopaedic shoeware for deformed feet. The final goal of the cognitive task analysis is to design a tutoring system for junior orthopaedic shoe technicians.

The first modelling view applied was the task modelling view. The main question to be answered in this phase was "what goals have to be accomplished" to provide shoeware. The outcome of this modelling view was two-fold: a task

model of the decomposed task and insight in the task environment. The method followed to reach these task modelling outcomes consisted of interviewing subject-matter experts, such as practising orthopaedic shoe technicians, orthopaedic shoe technicians functioning in organisational and management positions and rehabilitation physicians and by observing them performing their tasks.

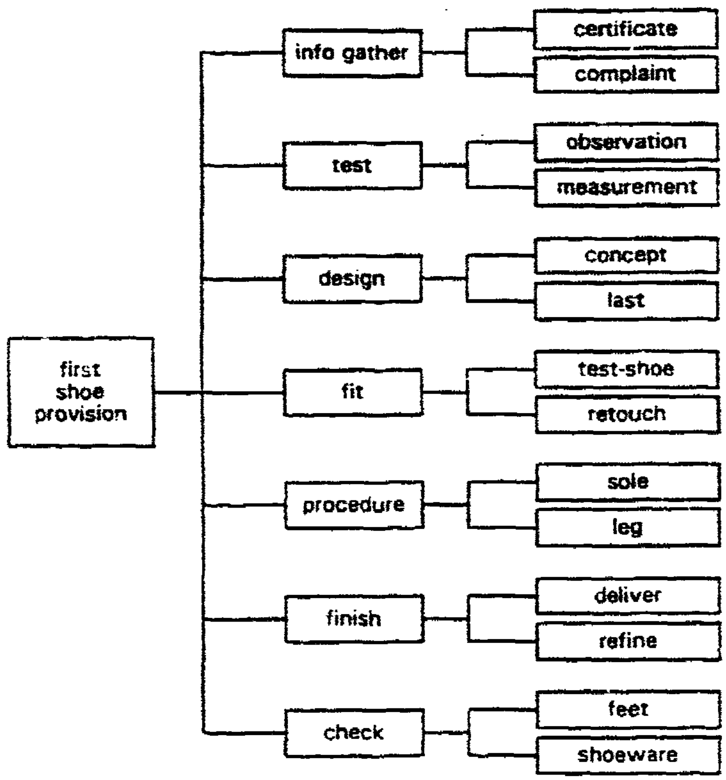

Fig. 4 Example of a task model of the decomposed task of providing orthopaedic shoeware.

The first outcome, the task model of the decomposed task is partly illustrated in Fig. 4. The main task of providing shoeware can be decomposed into the following general subtasks: gathering information, testing, designing, fitting, producing, finishing and checking. These subtasks can be decomposed again into the following subtasks: gathering information from the physicians, gathering information from the clients themselves, observing the clients' movements, measuring the clients' relevant foot parameters, designing the first shoe-concepts, designing shoe-lasts, fitting the clients' test-shoes, retouching the test-shoes, producing the shoe's soles, producing the shoe's legs, delivering the final shoe-products, refining the products (in case of few complaints, otherwise the preceding activities must be iterated), checking the clients' feet and the clients' shoes after some time. The task model is important for identifying problematic task elements and for gaining insight into the task domain.

The second outcome of the task modelling was to obtain information about the task environment. This information was obtained by confronting the subject-matter experts with the produced task model. They came up with exceptions in task execution which were influenced by the various situations under which the task could be executed; in doing so they gave the task analysts more insight in the context of the task and were able to indicate the problematic issues in orthopaedic shoe technic. The situations that make the task performer deviate from the task model, are situations in which a number of subtasks are skipped. This deviated task execution can be found in situations in which shoeware is provided to already known clients, in contrast to situations in which shoeware is provided to novel clients, the so-called first shoe provision. In providing shoeware to already known clients a number of subtasks can be skipped, because most information of the client is already gathered and relatively few changes have occurred since the first shoe provision. In further investigating this difference, it turned out that most problems occurred with first shoe provisions and that these problems often were restricted to the first three subtasks, which together form the "measurement taking process": information gathering, testing and designing. In the measurement taking process the shoe technician notes the client's problems, takes measurements of the feet and designs an initial shoe provision.

The second modelling view, knowledge modelling, was focusing on the output of the task modelling, in this case the three problematic subtasks of providing orthopaedic shoeware: information gathering, testing and designing. The relevant questions in this phase are "which performance norms are prescribed" and "what strategies and knowledge should be used in order to accomplish the goals of providing shoeware". In viewing these activities from a knowledge modelling point of view, in the first place procedural knowledge were to be identified. These procedural knowledge would show how expert shoe technicians approached the measurement taking process, and how they divided this process into an ordered set of subtasks. In order to be able to identify the task of providing orthopaedic shoeware as some kind of generic task more information was gathered about the task domain by interviewing subject-matter experts, such as orthopaedic shce technicians, rehabilitation physicians and orthopaedic surgeons and by observing them in carrying out their jobs, while being asked to think aloud. A global identification of two generic tasks was made first: diagnosis and design. As the outcome of the knowledge modelling phase a normative cognitive performance model was made on the basis of a limited number of verbal protocols and on the basis of the two generic tasks. The result was a merging of the diagnosis and the design task applied to domain-specific concepts. The result of this merging was a normative model or a coding scheme for verbal protocols to be obtained in the cognitive modelling phase.

For instance, one category of the coding scheme, which originates from the generic task of diagnosis, was "formulate hypotheses". This category refers to activities dealing with formulating hypotheses concerning the reduction of foot

functions, concerning the reduction of foot functionality and concerning the social limitations to the shoe client. A statement in a verbal protocol which refers to the category of formulating hypotheses concerning reduction of foot functions is: "if you see those pressure stains on the feet, you would expect that the client should have returned sooner (to the orthopaedic shoe technician)". The next category in the coding scheme was to test those hypotheses. In the normative model these categories of cognitive tasks, among others, must be carried out in order to provide a final shoe product.

In investigating the normative cognitive performance model of the tasks more thoroughly, the problems the junior orthopaedic shoe technicians encountered, were expected to be caused among other things by a lack of diagnostic knowledge. The assumption was that more experienced shoe technicians already had acquired this knowledge over the years, because they cooperated intensively with rehabilitation physicians and orthopaedic surgeons and that they had implicitly merged diagnosis and design knowledge in such a way that they were not aware they used this knowledge to deliver optimal orthopaedic shoeware. However, junior shoe technicians are also expected to know what kind of activities must be performed on the basis of the specific deformed feet of the client in order to deliver optimal orthopaedic shoeware.

The third modelling view, cognitive modelling, was focusing too on the three problematic subtasks of shoe provision: information gathering, testing and designing. The central question here was "what performance is displayed in practice by orthopaedic shoe technicians and especially by junior orthopaedic shoe technicians" in order to provide shoeware. The outcome of this modelling view was to produce performance models of these task performers and to compare these descriptive models with the normative performance model, produced in the knowledge modelling phase. This outcome was obtained by observing and analysing the task performers carrying out their tasks, while being asked to think aloud.

Three conditions of executing the task were investigated and compared with each other to obtain possibly different performance models. The first condition consisted of a situation in which the task was executed by an experienced orthopaedic shoe technician in cooperation with a rehabilitation physician. The second condition consisted of a situation in which the task was executed by an experienced orthopaedic shoe technician on his own. The third condition consisted of a situation in which the task was executed by a junior orthopaedic shoe technician on his own. In these conditions the task and the kind of foot deformation do not vary, only the task performers do by varying their type of expertise and by varying their level of expertise. In this way conclusions can be made about the differences in task execution found in the three different conditions. This gives us further insight in expert-novice differences and in the importance of collaborating with physicians. Knowing the problems junior

orthopaedic shoe technicians encounter, learning material can be constructed to develop a tutoring system.

6 GENERAL DISCUSSION

A framework for the analysis of—and examination of—cognitive tasks has been presented. This framework has been created, because an explicit definition of cognitive task analysis does not exist and because areas of research should be explored in the field of cognitive task analysis. Despite the fact that many techniques in the literature are labelled "cognitive task analysis", they show little or no resemblance with each other. This diversity is caused partly by the fact that each technique is developed to accomplish a specific goal.

Generally the following goals of cognitive task analysis can be found:
a Generating interface specifications
b Assessing and improving workload
c Describing the functional structure of a task domain for function allocation
d Designing training materials and generating training issues
e Diagnosing performance and predicting performance time
f Developing knowledge-based systems.

In order to apply cognitive task analysis in practice, it is necessary to be explicit about the way the goals of the cognitive task analysis can be accomplished. However, we have already mentioned that defining cognitive task analysis as modelling the task, the knowledge and the human cognition is a time-consuming process. Therefore the modelling views can only be worked out with equal strength in every application of cognitive task analysis at high costs; not all views are equally important in accomplishing the goal of each analysis. This means that the contribution of each of the modelling views to cognitive task analysis can vary. The framework for cognitive task analysis gives no practical guidelines about the weight of each modelling view in cognitive task analysis. The process of determining what contribution each modelling view must have and what analysis technique must be selected strongly depends on the goals of the analysis. These issues can be especially interesting for applied research. Table I illustrates a possible relation between the goals of cognitive task analysis and the three modelling views. This relation and the relation between modelling views and analysis could be investigated further in the future.

Table I Proposed relative weight (low, medium, high) of the modelling views for the various goals of cognitive task analysis.

	modelling perspectives		
goals of cognitive task analysis	task modelling	knowledge modelling	cognitive modelling
generate interface specifications	low	medium	high
improve workload	low	medium	high
functional structure	high	medium	low
designing training material	low	medium	high
predicting preformance	low	medium	high
developing knowledge-based systems	low	high	medium

= low
= medium
= high

Another interesting issue for applied research is to investigate the order in which the three modelling views in cognitive task analysis could be used best and to investigate what kinds of modelling views and techniques can be applied best to analyse particular tasks and task environments. From this point of view various dimensions (e.g. the degree of structuredness of a task) could be created to characterize each task and to select a modelling view or even an analysis technique on the basis of the identified task characteristics. This pre-analysis phase could be carried out before the actual cognitive task analysis begins. It would be convenient to check a couple of standard items against a given task and to decide, on the basis of this result, what kind of modelling view or modelling technique can best be used. An important goal of doing this kind of applied scientific research is to develop practical guidelines for selecting appropriate analysis techniques on the basis of the goals of the analysis and on the basis of identified task characteristics.

Fundamental research could focus more on the bridging of the gap between one sight of the camp, the task modelling view, and the other sight of the camp, the cognitive modelling view. It is interesting to invent a way in which task requirements could be acquired in such a way that they, together with the task's goals, can easily be used to make predictions about cognitive performance. The idea of focusing not only on the task modelling and cognitive modelling view but on the knowledge modelling view as well, in which task requirements and performance norms are important, is shared with Essens, Fallesen, McCann, Cannon-Bowers and Dörfel (1994). Within the context of our recent research of

decision making in teams the acquisition of task requirements and performance norms also plays an important role in allocating tasks and subtasks to specific functions of the team. The assessment of cognitive performance of the team members should preferably be made *before* having analyzed the (cognitive) performance of the members in practice, because this often can be done only at high costs. Members of teams are cooperating with each other to accomplish one main goal. In order to be able to assess the cognitive performance of the members of the team or of the decision maker the main goal must be decomposed in various subgoals and their task requirements must be obtained. If techniques are found to obtain task requirements efficiently, further research must focus on the prediction of cognitive performance of team members out of the subgoals and the requirements of the task.

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Soesterberg, 11 July 1994

Drs. E.J.H.M. Merkelbach

APPENDIX

In order to gain a complete view on the relevant literature, a literature search was carried out within the following databases:

* NTIS, 1964-1993/Sep B2, keywords: cognitive processes, task analysis and the combination of these two keywords;
* SOCIAL SCISEARCH, 1972-1993/Aug W1, keywords: task analysis, cognitive? and the combination of these two keywords;
* TDCK, keywords: cogniti* and the Dutch word for task analysis ("taakanalyse") or task adj analysis;
* PsycINFO, 1967-1993/Sep, keywords: task analysis, cognitive? and a combination of these two keywords; models or methodology or measurement or methods and a combination of the three keywords;

The result of this literature search was a total amount of 82 references. Most of these references were not appropriate to be pursued, because they were either too old (published before 1985), too vague or too specific (e.g. educational analyses). From the other references the following techniques or methodologies were considered to be appropriate to be studied in the perspective of this report:

Analysis for Task Object Modelling (ATOM) (Walsh; in Diaper, 1989)
Contextual Module Analysis (CMA) (Tennyson, Elmore & Snyder, 1992)
Cognitive Reliability Analysis (CRA) (Hollnagel, 1991)
Cognitive Tasks: A Meta-Analysis of Methods (Alm, 1992)
Cognitive Task Analysis (CTA) (Bainbridge, 1989)
Cognitive Task Analysis (CTA) (Klein, 1993)
Cognitive Task Analysis (CTA) (Leplat, 1988)
Cognitive Task Analysis (CTA) (Moray, Sanderson & Vicente, 1992)
Cognitive Task Analysis (CTA) (Neerincx & Griffioen, 1993)
Cognitive Task Analysis (CTA) (Schaafstal & Schraagen, 1992)
Integrated Task Analysis Model (ITAM) (Ryder & Redding, 1993)
Jackson System Development (JSD) (Jackson, 1983)
Goals Operators Methods and Selection Rules (GOMS) (Card, Moran & Newell, 1983)
Hierarchical Task Analysis (HTA) (Annett & Duncan, 1967)
Knowledge Analysis of Tasks (KAT) (Johnson; in Diaper, 1989)
Modern Structured Analysis (MSA) (Yourdon, 1989)
Task-Action Grammar (TAG) (Payne & Green; in Diaper, 1989)
Task Analysis for Knowledge Descriptions (TAKD) (Diaper, 1989)
Task-based Cognitive Modelling (Mullins & Treu, 1993).

Table II illustrates the emphasis the techniques, in our opinion, place upon each of the modelling views.

Table II Proposed weight (high, medium, low, no) of the analysis techniques for the modelling views of cognitive task analysis.

	modelling perspectives				
analysis techniques	task modelling	knowledge modelling		cognitive modelling	
		task oriented	knowledge oriented	task oriented	knowledge oriented
ATOM Walsh	LOW	LOW	HIGH	NO	NO
CMA Tennyson et al.	NO	LOW	HIGH	NO	MEDIUM
CRA Hollnagel	MEDIUM	HIGH	LOW	LOW	LOW
CTA Alm	MEDIUM	LOW	NO	HIGH	NO
CTA Bainbridge	LOW	HIGH	NO	LOW	NO
CTA Klein	LOW	HIGH	HIGH	HIGH	HIGH
CTA Leplat	NO	HIGH	MEDIUM	HIGH	MEDIUM
CTA Moray et al.	LOW	HIGH	LOW	HIGH	LOW
CTA Neerincx et al.	MEDIUM	NO	NO	HIGH	HIGH
CTA Schaafstal et al.	NO	MEDIUM	LOW	HIGH	MEDIUM
GOMS Card et al.	LOW	MEDIUM	LOW	HIGH	LOW
HTA Annett et al.	HIGH	MEDIUM	LOW	NO	NO
ITAM Ryder et al.	LOW	HIGH	HIGH	MEDIUM	MEDIUM
JSD Jackson	LOW	LOW	HIGH	NO	NO
KADS Schreiber et al.	LOW	HIGH	HIGH	LOW	LOW
KAT Johnson	MEDIUM	HIGH	HIGH	LOW	LOW
MSA Yourdon	HIGH	LOW	MEDIUM	NO	NO
TAG Payne et al.	MEDIUM	HIGH	MEDIUM	NO	NO
TAKD Diaper	HIGH	NO	NO	LOW	HIGH
TCM Mullins et al.	HIGH	NO	NO	MEDIUM	NO

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15. ABSTRACT (MAXIMUM 200 WORDS, 1044 BYTE)

The goal of this study was to examine similarities and differences between various types of cognitive task analysis and, if possible, to infer some framework in which the areas for further research should become clear. The result of this study is a framework which integrates three views on cognitive task analysis: task, knowledge and cognitive modelling. For each view, prototypical task analysis techniques are presented respectively: Hierarchical Task Analysis (HTA), Knowledge Analysis and Documentation System (KADS) and Goals Operators Methods and Selection rules (GOMS).
The task modelling view and the cognitive modelling view are already known in the cognitive task analysis domain. The task modelling view concentrates on the decomposition of tasks into goals and subgoals. The cognitive modelling view concentrates on the cognitive performance of the task. The knowledge modelling view, however, is a relatively new element in the research area of cognitive task analysis.
Within the knowledge modelling view, it is recommended by the framework to gain information about the requirements of the task. Those requirements can have a strong influence on the cognitive performance of the task and, therefore, within the framework of cognitive task analysis, it is advised to examine task requirements before starting to analyze the cognitive performance of the task. Many types of cognitive task analysis focus too much on the cognitive performance of a task, without paying much attention to the requirements of the task.
Further research in this area is therefore necessary to bridge the gap between one sight of the camp, the task modelling view, and the other sight of the camp, the cognitive modelling view. An interesting work of research could be to invent a way in which task requirements are acquired in such a way that they, together with the task's goals, can easily be used to make predictions about cognitive performance.

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